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A design study of silicone insulated transformers

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A DESIGN STUDY OF SILICONE INSULATED TRANSFORMERS

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A DESIGN STUDY OF SILICONE
INSULATED TRANSFORMERS

by

Joseph R. Tucker
Commander, United States Navy

Submitted in partial fulfillment
of the requirements
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in
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PREFACE

In recent years the Navy has become very interested in any method that will decrease the size of various types of electrical rotating and stationary machinery and also to increase their reliability under normal operating conditions. An examination of data from Naval new construction vessels will indicate why this has become important. These new vessels are almost twice the size of their pre World War II prototypes. Much of this increase in size may be attributed to the large amount of electronic, sonar, and radar equipment which have been placed upon them, no small part of which is electrical equipment, which is, of course, the power source for the equipment. If some method could be devised to decrease the size of this equipment, it would be advantageous to the Naval Constructors in their search of methods to keep their new construction vessels within their respective size requirements.

Two methods have been advocated as possibilities in this matter. Both are theoretically excellent possibilities, but both would involve major changes in our present shipboard electrical layouts. The first of these methods is an increase in the voltage and frequency values to 1000 volts and 400 cycles. The second method is the introduction of higher operating temperatures in electrical machines by the use of new type insulating materials, the most promising of which seems to be the silicone family of insulation products.

In 1948 as partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Electrical Engineering at the United States Naval Postgraduate School, Lieutenant Commander James Mercer, U. S.

Navy and Lieutenant Commander Harborough Irwin Lill, Jr., U. S. Navy, made a comparison of 400 cycle 1000 volt transformers to 60 cycle 450 volt transformers. The purpose of this thesis is to extend the work of Mercer and Lill so as to include comparisons of silicone insulated transformers, both 60 and 400 cycle, to ordinary 60 and 400 cycle transformers, and to each other.

The work on this thesis was done in the early months of 1949 at the United States Naval Postgraduate School, Annapolis, Maryland under the direction and guidance of Professor C. V. O. Terwilliger, Head of the Department of Electrical Engineering. To him the author is greatly indebted for all help and assistance which he has so cheerfully given.

The author is also greatly indebted to Lieutenant Commander James Mercer, U. S. Navy and Lieutenant Commander Harborough Irwin Lill, U. S. Navy for the guidance which their thesis has given him.

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INTRODUCTION

At the present time there are two types or classes of insulation in general use in electrical equipment. These types are standard among all leading manufacturers and designers and are known as Class A and Class B insulating materials. Class A materials include cotton, paper, and similar organic materials impregnated or bonded with organic resins and varnishes. Class B materials include asbestos, fiberglass, mica, and similar inorganic materials fabricated with organic resins and varnishes. In general practice Class A insulation can usually be used up to temperatures of $105^{\circ}C$ and Class B insulation up to temperatures of about $130^{\circ}C$. United States Navy requirements and limits, however, are $90^{\circ}C$ and $110^{\circ}C$ respectively for Classes A and B materials. It should be borne in mind that all general type transformers in use today, with very few exceptions, are constructed of Class A or Class B insulation and are therefore subject to the above temperature limitations.

If insulation materials are subjected to temperatures in excess of the temperatures indicated in the preceding paragraph for even short periods of time, they will deteriorate quite rapidly. This is due to the inherent low temperature characteristics of the organic bonding material. If we could conceivably find a bonding agent which possessed the necessary insulation qualities and also remained stable up to temperatures of say $200^{\circ}C$ or even slightly higher, we could operate our electrical equipment at higher temperatures. This factor in itself is of no advantage, as making a machine "hot" is usually a distinct liability. The virtue of this ability to raise temperature

limits lies in the subsequent benefits which this feature makes possible. Among these benefits are:

1. To obtain increased life of insulation when it is desired to maintain conventional size, weight, and temperatures.

2. To permit operation in high ambient temperatures such as might be encountered in tropical climates or in the boiler and engine rooms of Naval ships.

3. To permit prolonged overloads without unreasonable damage to the insulation.

4. To make machines that are nearly fire-proof.

5. To reduce size and weight of machines through increases in normal load temperature rises.

The introduction of silicone insulating materials would seem to be the answer to the problem of finding a bonding agent which possesses the necessary insulation qualities as well as the high temperature stability feature. There are other factors, of course, which must be considered other than the high temperature characteristic, but these will not be considered other than to mention them later in this paper.

Of the above benefits which are made possible through the use of high temperature insulating materials, the one that we are most interested in is that of reducing the size and weight of machines, particularly the transformer. Upon investigating the possibilities of comparing the design features of a silicone insulated machine with that of a conventionally insulated machine, the author chanced upon the transformer thesis written by Lieutenant Commander Mercer and Lieutenant Commander Lill and considered this an excellent oppor-

tunity for making a comparison of conventional and silicone insulated transformers.

In order to properly compare these various types of transformers, it was necessary that the author make substantially the same assumptions in this thesis as were made in the non silicone thesis. These assumptions bring the problem down to one of bare fundamentals, but they are necessary in order to make an adequate comparison. These assumptions and considerations include:

1. The use of ARMCO Tran-cor XXX, a new type of cold rolled oriented silicon steel, as the core material. This steel was used in laminations .014 inches thick, the standard size for transformers. Tran-cor XXX has very good electrical properties and along with other similar types manufactured by other steel companies, have tended to reduce core weights about 15 to 20%. Its use in the present transformer insures the smallest weight of core possible for the given rating.

2. The transformers designed are 10 KVA transformers of the core type with two coils on each leg and inner and outer coils respectively in series. Voltage ratio is one-to-one.

3. The 60 cycle transformers are designed as 450 volt machines and the 400 cycle transformers as 1000 volt machines.

4. It is assumed that copper losses equal core losses.

5. Flux densities are varied from 60,000 to 100,000 lines per square inch for 60 cycle calculations and from 20,000 to 65,000 lines per square inch for 400 cycle calculations. This will give desired values above and below the normal operating flux densities for the different frequencies, and allow a comparison of

characteristics over the entire possible operating range.

6. Silicone resin impregnated glass insulation was used on the conductors with a thickness of 5 mils. This is quite adequate to give a large factor of safety from an insulation standpoint.

7. Power factor of one is assumed.

8. All clearances between coils and between coils and core are assumed to be one quarter of an inch. The window dimensions of the core are 4/3 and 10/3 the width of the core leg which is assumed square.

9. For volume computations a cylindrical shaped transformer was assumed with a two inch clearance between case and windings, and a four inch vertical clearance between core and case. The weight of the case and connectors was neglected, the only weight considerations being those of copper and silicon iron core.

10. A stacking factor K of .96 was used. This is believed to be slightly high, but it was used to comparative purposes.

11. An operating temperature of $200^{\circ}C$ was used for all computations. This gave from Smithsonian Tables a value for copper resistance at this temperature of 17.80 ohms/circular mil foot or 1.4833 ohms/circular mil inch which was used in this computation. This value was checked by various formulas found in electrical handbooks and manuals and found to check very closely. It should be mentioned here that Mercer and Lill, in their computations assumed a resistance of copper of 12 ohms/circular mil foot. This corresponds to a temperature of about $60^{\circ}C$. So the non-silicone transformers are actually designed for an approximate operating temperature maximum of $60^{\circ}C$. Thus, the comparisons in this paper are actually comparisons

between transformers designed to operate at 60°C and transformers designed to operate at 200°C. The 60°C value is actually less than that normally used for Class A insulation.

12. All transformers were designed, by trial and error, for maximum efficiency obtainable for given clearance values. Basic formulae used are included in the sample calculations which appear at the end of this paper.

In all the computations the flux density was considered the chief variable and values for efficiency, weight of iron, weight of copper, total weight of iron and copper, exciting current and volume were computed and plotted against the flux density values. These curves also appear at the end of this paper.

CONCLUSIONS

In general, it may be stated that the use of silicone insulation for higher temperature operation has an advantageous effect on all factors considered in this analysis. Efficiencies of silicone insulated transformers were higher than their non silicone prototypes. Weights of iron and copper and total weight were much smaller for the silicone transformers as was the volume of the transformer as we would expect. Exciting currents were also proportionately less for both 60 cycle and 400 cycle designs. It is evident that we cannot expect as large percentage gains in weight and volume at the operating flux densities by the use of the silicone insulation as we do from the use of 400 cycle over 60 cycle. We can, however, obtain better size and

volume figures as the below analysis will show. In the following
data obtained from the curves and taken at the optimum flux density
for each cycle (assumed 75,000 lines/square inch for 400 cycle) we
can get an excellent comparison of the various transformers.

	60 CYCLE	60 CYCLE SILICONE	400 CYCLE	400 CYCLE SILICONE
Efficiency	98.95	99.065	98.50	98.68
Copper weight	186	158	61	50
Iron weight	119	102	63	54
Total weight	305	260	126	106
Volume	3.45	3.10	1.07	.94
l_o-% of I	1.32	1.20	.92	.81

From this data we may make the following observations:

1. The efficiencies of the 400 cycle transformers are less
than the efficiencies of the 60 cycle transformers, but for each
frequency, the silicone transformer has greater efficiency than the
non silicone.

2. The copper weight of a 400 cycle silicone transformer
is only 26.9% of that of a 60 cycle non silicone transformer. In the
60 cycle machines the silicone machine used only .848 the amount of
copper of the non silicone machine, and in the 400 cycle frequency
range the same proportion is .819.

3. The total weight of copper and iron for the 400 cycle
silicone transformer is only 34.7% that of a 60 cycle non silicone
transformer. In the 60 cycle machines the silicone transformer has
only .852 the weight of the non silicone, and in the 400 cycle machines

the total weight of the silicone is only .839 that of the non silicone.

4. The volume of a 400 cycle silicone transformer is only .273 the volume of a 60 cycle non silicone transformer. Ratios between silicone and non silicone transformers volumes for 60 cycle and 400 cycle are respectively .898 and .878.

5. 400 cycle exciting currents are less than 60 cycle exciting currents on a percentage basis, and silicone exciting currents are proportionately less than the non silicone exciting currents.

6. In general we may say that a combination of silicone insulation and 400 cycles tends to slightly lower the efficiency, lower the exciting current by 40%, decrease the copper and iron weight to a factor of about .35, and decrease the volume to a factor of about .28 as compared to a normal 60 cycle non silicone transformer.

The above data is of course only approximate and many factors have been ignored in its derivation which would cause a finished design problem to depart from this data, but it does show a decided trend, and the differences obtained between 60 and 400 cycle and between silicone and non silicone designs are large enough to cause pilot models to be built and developmental contracts to be let for a thorough study of these features.

Not all of the advantages of silicones have as yet been brought out nor have its disadvantages been surveyed. As a matter of fact, silicone insulating material has not as yet been fully evaluated as an insulating material, or as a major factor in the electrical industry. This evaluation is being carried on rapidly, however, and the U. S. Navy has shown great interest in the subject as evidenced by the fact

that it will on certain contracts allow the contractor latitude to
use silicone insulation if he meets the other requirements of the
contract. Some of the advantages which we have not mentioned with
regards to silicones are its moisture resistance, inflammability,
chemical reagent resistance, dielectric strength, and high power
factor. Some of its disadvantages are cost and availability, lack of
abrasion resistance, loss of dielectric strength after mechanical
deformation, curing time, and volatility in totally enclosed rotating
electrical machines. As will be seen few of these disadvantages are
of great importance in the design of a transformer which has no
moving parts, and therefore not subject to centrifugal stresses.

A transformer designed using silicone insulation would at present
have to be a dry type and air cooled transformer. It would therefore
probably be used for smaller types of distribution transformers. The
reason for this is that at present the silicones developed are acted
upon by hydrocarbon and also silicone oils. Thus, an oil cooled
silicone insulated transformer would not be practical at present.
This feature is being investigated from two different angles, the
development of a silicone not affected by oil, and the development
of other liquid coolants other than oil which the present silicones
will not attack or be attacked by. The solution of this problem
should not be difficult, and in the future, I think we can look for-
ward to the production of a large number of silicone insulated
transformers for special uses of both the wet and dry types.

1.	Flux Density	60000	65000	70000
2.	Efficiency	99.16	99.14	99.096
3.	Core Loss == Cu Loss	42	43	45.3
4.	Watts/cubic inch	.083	.0926	.1088
5.	Vol Iron	506	464	417
6.	D^3	39.5	36.25	32.5
7.	D	3.406	3.309	3.188
8.	Window Height	11.353	11.03	10.626
9.	Window Width	4.54	4.412	4.2504
10.	Coil Height	10.853	10.53	10.126
11.	Turns/ Coil	126.6	123.7	123.7
12.	Coil Space	1.645	1.581	1.5002
13.	Est. Width Inner Coil	.68	.68	.60
14.	Mean Length Turn Inner Coil	17.334	16.95	16.222
15.	Copper Length Inner Coil	2195	2095	2007
16.	Resistance Inner Coil	.0212	.0217	.02286
17.	Resist./ inch – Inner Coil	.00000967	.00001034	.00001138
18.	Copper Area – Inner Coil	.0549	.0512	.0465
19.	Turns/ Layers Inner Coil	42/3	42/3	42/3
20.	Inner Coil Conductor Height	.2485	.241	.231
21.	Inner Coil Conductor Width	.2205	.2125	.201
22.	Inner Coil Width	.6915	.6675	.633
23.	Space for Outer Coil	.9535	.9135	.8672
24.	Mean Length of Turn –Outer Coil	24.124	23.456	22.612
25.	Copper Length – Outer Coil	3050	2900	2795
26.	Resistance – Outer Coil	.0212	.0217	.02286
27.	Resist/ inch – Outer Coil	.00000695	.00000748	.00000819
28.	Copper Area – Outer Coil	.0762	.0707	.0645
29.	Turns/ Layer – Outer Coil	42/3	42/3	42/3
30.	Outer Coil Conductor Height	.2485	.241	.231
31.	Outer Coil Conductor Width	.3065	.293	.279
32.	Outer Coil Width	.9495	.909	.867
33.	Volume of Iron	506	464	417
34.	Wgt. of Iron	140	128.5	115.5
35.	Wgt. of Copper	227.5	201.5	176.7
36.	Length Mean Flux Path	42.506	41.294	39.783
37.	Ampere Turns/ inch	.71	.82	.87
38.	Ampere Turns/ Lap Joint	2.5	3.0	4.0
39.	Total Ampere Turns	40.2	45.85	50.6
40.	I_{mag}	.159	.1852	.205
41.	$I_{e/h}$	.0933	.0956	.1007
42.	I_o	.184	.208	.228
43.	$I_o\%$ Full Load I	.827	.934	1.024
44.	Volume of Transformer – ft^3	3.87	3.62	3.32
45.	Weight of Transformer	367.5	330	292.2

75000	80000	85000	90000	95000	100000
99.065	99.02	98.99	98.947	98.90	98.848
46.75	49	50.5	52.65	55	57.6
.123	.1402	.1583	.1795	.203	.229
380	349.5	319	293.5	271	252
29.7	27.3	24.95	22.9	21.16	19.67
3.097	3.011	2.922	2.841	2.766	2.6995
10.323	10.037	9.74	9.47	9.22	8.998
4.1292	4.0148	3.896	3.788	3.688	3.5992
9.823	9.537	9.24	8.97	8.72	8.498
122.7	121.7	121.8	121.5	121.2	121.3
1.4396	1.3824	1.323	1.269	1.219	1.1746
.60	.60	.54	.52	.50	.50
15.858	15.504	14.968	14.634	14.204	13.938
1945	1885	1822	1778	1720	1690
.0236	.02475	.0255	.0266	.0278	.0291
.00001215	.00001314	.000014	.00001497	.00001615	.00001723
.0436	.0404	.03775	.0354	.0327	.0307
41/3	41/3	41/3	41/3	41/3	41/3
.2295	.2225	.215	.209	.2025	.197
.19	.1815	.1755	.1695	.1612	.156
.60	.5745	.5565	.5385	.5136	.498
.8396	.8079	.7665	.7305	.7054	.6766
21.958	21.364	20.748	20.204	19.654	19.198
2695	2600	2530	2455	2380	2330
.0236	.02475	.0255	.0266	.0278	.0291
.00000877	.00000951	.0000101	.00001084	.00001168	.0000125
.0604	.0555	.0525	.0489	.04535	.0424
41/3	41/3	41/3	41/3	41/3	41/3
.2295	.2225	.215	.209	.2025	.197
.263	.250	.2445	.2335	.224	.2145
.819	.780	.7635	.7305	.702	.6735
380	349.5	319	293.5	271	252
105.2	96.7	88.2	81.1	74.9	69.6
159.8	141.9	130.0	118	10.6	96.9
38.654	37.564	36.462	35.456	34.516	33.684
.95	1.04	1.15	1.30	1.68	2.55
6.1	8.0	10.6	13.5	17/8	24.9
61.1	71.2	84.4	100.15	129.2	185.6
.249	.292	.347	.412	.532	.764
.1053	.109	.1123	.1172	.1222	.1282
.270	.312	.365	.428	.546	.775
1.213	1.4	1.637	1.92	2.45	3.48
3.07	2.87	2.685	2.51	2.36	2.23
2.65	238.6	218.2	199.1	180.9	166.5

1.	Flux Density	20,000	25,000	30,000
2.	Efficiency	99.245	99.075	98.945
3.	Core Loss equals Cu Loss	37.75	46.25	52.75
4.	Watts/cubic inch	.16	.275	.4
5.	Vol Iron	236	168.2	131.9
6.	D^3	18.46	13.13	10.29
7.	D	2.643	2.359	2.176
8.	Window Height	8.81	7.863	7.253
9.	Window Width	3.524	3.1452	2.9012
10.	Coil Height	8.31	7.363	6.753
11.	Turns/Coil	209.5	210.5	207
12.	Coil Space	1.137	.9476	.8256
13.	Est. Width Inner Coil	.48	.40	.36
14.	Mean Length Turn Inner Coil	13.652	12.266	11.404
15.	Copper Length Inner Coil	2860	2580	2360
16.	Resistance Inner Coil	.094375	.1156	.1319
17.	Resist./inch – inner coil	.0000329	.0000449	.0000558
18.	Copper Area – Inner Coil	.01605	.0118	.009475
19.	Turns/ Layers Inner Coil	53/4	53/4	52/4
20.	Inner Coil Conductor Height	.1468	.129	.1199
21.	Inner Coil Conductor Width	.1093	.0914	.079
22.	Inner Coil Width	.4772	.4056	.356
23.	Space for Outer Coil	.6598	.542	.4696
24.	Mean Length of Turn – Outer Coil	18.797	16.836	15.574
25.	Copper Length – Outer Coil	3940	3550	3210
26.	Resistance – Outer Coil	.094375	.1156	.1319
27.	Resist/ inch – Outer Coil	.0000239	.0000325	.0000411
28.	Copper Area – Outer Coil	.0221	.01624	.01288
29.	Turns/ Layer – Outer Coil	53/4	53/4	52/4
30.	Outer Coil Conductor Height	.1468	.129	.1199
31.	Outer Coil Conductor Width	.1506	.1257	.1073
32.	Outer Coil Width	.6424	.5428	.4692
33.	Volume of Iron	236	168.2	131.9
34.	Wgt. of Iron	65.2	46.5	36.5
35.	Wgt. of Copper	85.5	56.7	41.2
36.	Length Mean Flux Path	32.988	29.446	27.158
37.	Ampere Turns/ inch	.245	.40	.45
38.	Ampere Turns/ Lap Joint	.5	.6	.75
39.	Total Ampere Turns	10.08	14.19	15.22
40.	I_{mag}	.02405	.0336	.0367
41.	$I_{e,h}$	.03775	.04625	.05275
42.	I_o	.0446	.0572	.0612
43.	I_o-% Full Load I	.446	.572	.612
44.	Volume of Transformer – ft3	2.12	1.638	1.372
45.	Weight of Transformer	150.7	103.2	77.7

35,000	40,000	45,000	50,000	55,000	60,000	65,000
98.86	98.76	98.68	98.59	98.49	98.40	98.30
57	62	66	70.5	75.5	80	85
.525	.67	.82	.99	1.19	1.41	1.64
108.7	92.6	80.5	71.2	63.4	56.8	51.8
8.49	7.24	6.285	5.565	4.96	4.435	4.05
2.04	1.935	1.845	1.772	1.705	1.643	1.594
6.80	6.45	6.15	5.906	5.683	5.477	5.313
2.72	2.58	2.46	2.362	2.273	2.191	2.125
6.3	5.95	5.65	5.406	5.183	4.977	4.813
200.2	195.5	191.3	187	183.5	180.5	177.3
.735	.665	.605	.556	.5115	.4705	.4375
.32	.29	.26	.24	.22	.20	.19
10.74	10.26	9.77	9.448	9.12	8.802	8.576
2158	2002	1870	1765	1673	1588	1520
.1425	.155	.165	.176	.189	.20	.2125
.0000661	.0000774	.000088	.0000998	.0001128	.000126	.00014
.00799	.00684	.006	.0053	.0047	.0042	.00379
50/4	49/4	48/4	47/4	62/3	61/3	60/3
.1160	.1116	.1077	.105	.0735	.0716	.0702
.0689	.0613	.0558	.0505	.0638	.05865	.0539
.3156	.2852	.2632	.2420	.2214	.206	.1917
.4194	.3798	.3418	.3140	.2901	.2645	.2458
14.61	13.88	13.26	12.738	12.27	11.852	11.506
2930	2715	2538	2380	2250	2140	2040
.1425	.155	.165	.176	.189	.20	.2125
.0000486	.0000571	.000065	.000074	.0000839	.0000934	.0001042
.0109	.00928	.00814	.00716	.00631	.005665	.00508
50/4	49/4	48/4	47/4	62/3	61.3	60/3
.116	.1116	.1077	.105	.0735	.0716	.0702
.094	.0833	.0755	.0681	.0859	.0788	.0723
.416	.3772	.3420	.3124	.2877	.2664	.2469
108.7	92.6	80.5	71.2	63.4	56.8	51.8
30	25.6	22.3	19.7	17.5	15.7	14.3
31.7	25.1	20.5	17.0	14.2	12.1	10.4
25.46	24.16	23.02	22.116	21.272	20.506	19.886
.50	.57	.60	.67	.70	.77	.82
.8	.9	1.0	1.1	1.4	2.2	3.0
15.93	17.35	17.812	19.21	20.5	24.6	28.3
.0396	.0444	.0465	.0513	.0558	.0682	.0796
.057	.062	.066	.0705	.0755	.080	.085
.0695	.0763	.0808	.0872	.094	.1052	.1164
.695	.763	.808	.872	.94	1.052	1.164
1.186	1.06	.963	.883	.815	.756	.71
61.7	50.7	42.8	36.7	39.7	27.8	24.7

60 CYCLE

Flux Density	60,000	65,000	70,000
Efficiency	99.033	99.024	98.972
Iron Wgt.	161.7	145.8	130.8
Cu Wgt.	277.5	240.5	212.5
I_o - % of I	.979	1.05	1.15
Wgt. of Iron and Cu	439.2	386.3	343.3
Vol - ft^3	4.29	4.03	3.68

400 CYCLE

Flux Density	20,000	25,000	30,000
Efficiency	99.15	98.947	98.8
Iron Wgt.	73.4	52.1	41.4
Cu Wgt.	101.2	68.3	48.4
I_o - % of I	.504	.646	.730
Wgt. of Iron and Cu	174.6	120.4	89.8
Vol - ft^3	2.33	1.794	1.500

SILICONE THESIS (MERCER AND LILL)

80,000	85,000	90,000	95,000	100,000
98.902	98.858	98.805	98.75	98.689
108.3	99.8	91.9	85.1	78.8
167.7	152.8	145.6	126.0	114.3
1.57	1.84	2.15	2.73	3.89
276	252.6	237.5	211.1	193.1
3.16	2.95	2.72	2.60	2.46

35,000	40,000	45,000	50,000	55,000	60,000	65,000
98.7	98.6	98.5	98.42	98.3	98.2	98.1
34.3	28.8	25.2	22	19.8	17.62	16
38.4	30.3	24.7	20.55	17.4	14.7	12.8
.786	.856	.912	.97	1.05	1.17	1.252
72.7	59.1	49.9	44.55	37.2	32.32	28.8
1.31	1.158	1.045	.957	.883	.82	.765

FIG. 1

Fig 2

Weight–Pounds (vertical axis)

Flux Density – Kiloline/Square Inch (horizontal axis)

60 CYCLE
60 CYCLE SILICONE

TOTAL
TOTAL
COPPER
COPPER
IRON
IRON

Fig 3

TOTAL

TOTAL

400 CYCLE

400 CYCLE SILICONE

COPPER

COPPER

IRON

IRON

WEIGHT - POUNDS

200

160

120

80

40

0

FLUX DENSITY - KILOLINES/ SQUARE INCH

0   10   20   30   40   50   60   70   80

Fig 4. — Graph of I % of I full load versus Flux Density – Kilolines/Square Inch, showing Non Silicone and Silicone curves for 60 Cycle and 400 Cycle.

Fig 5 · 19
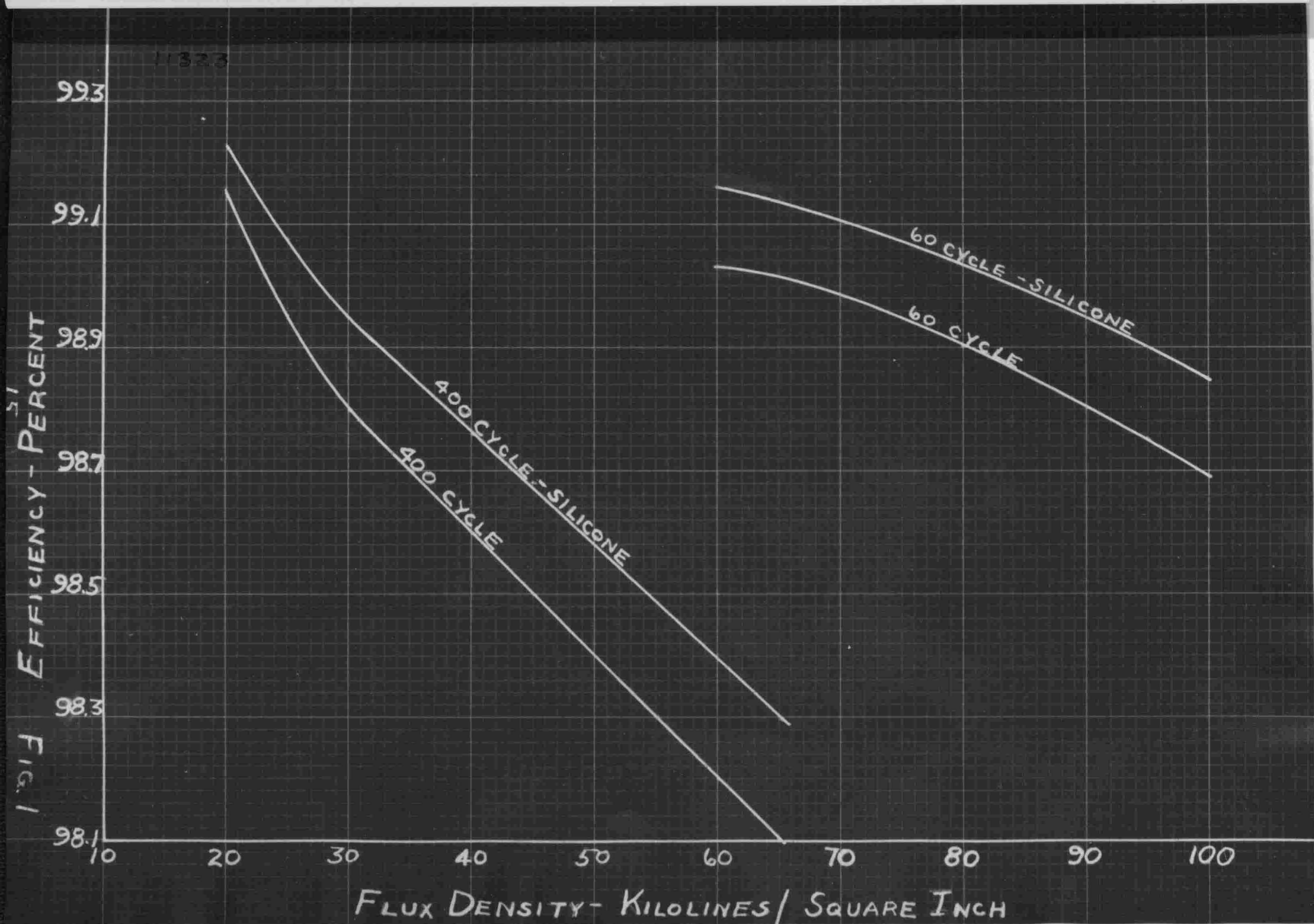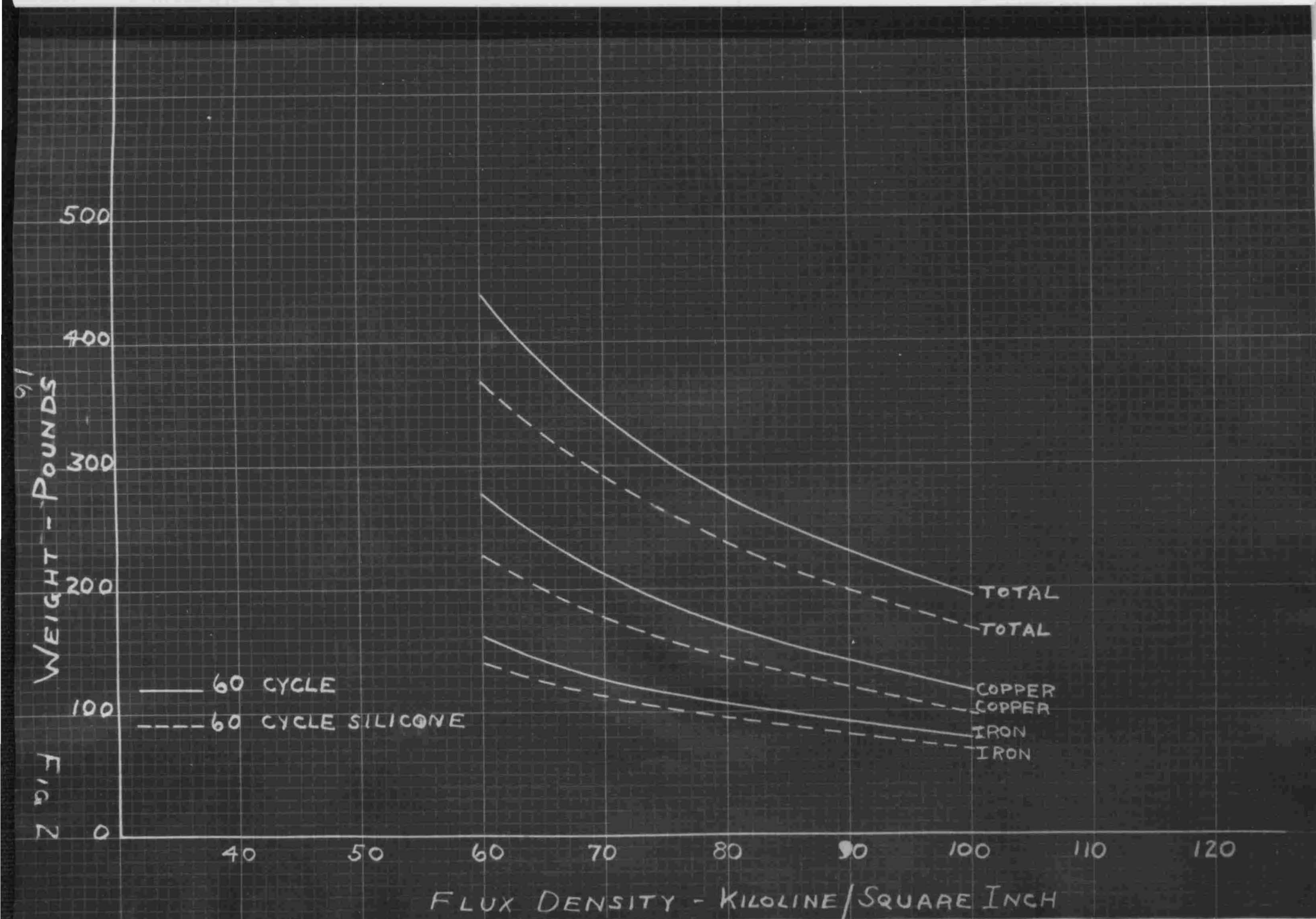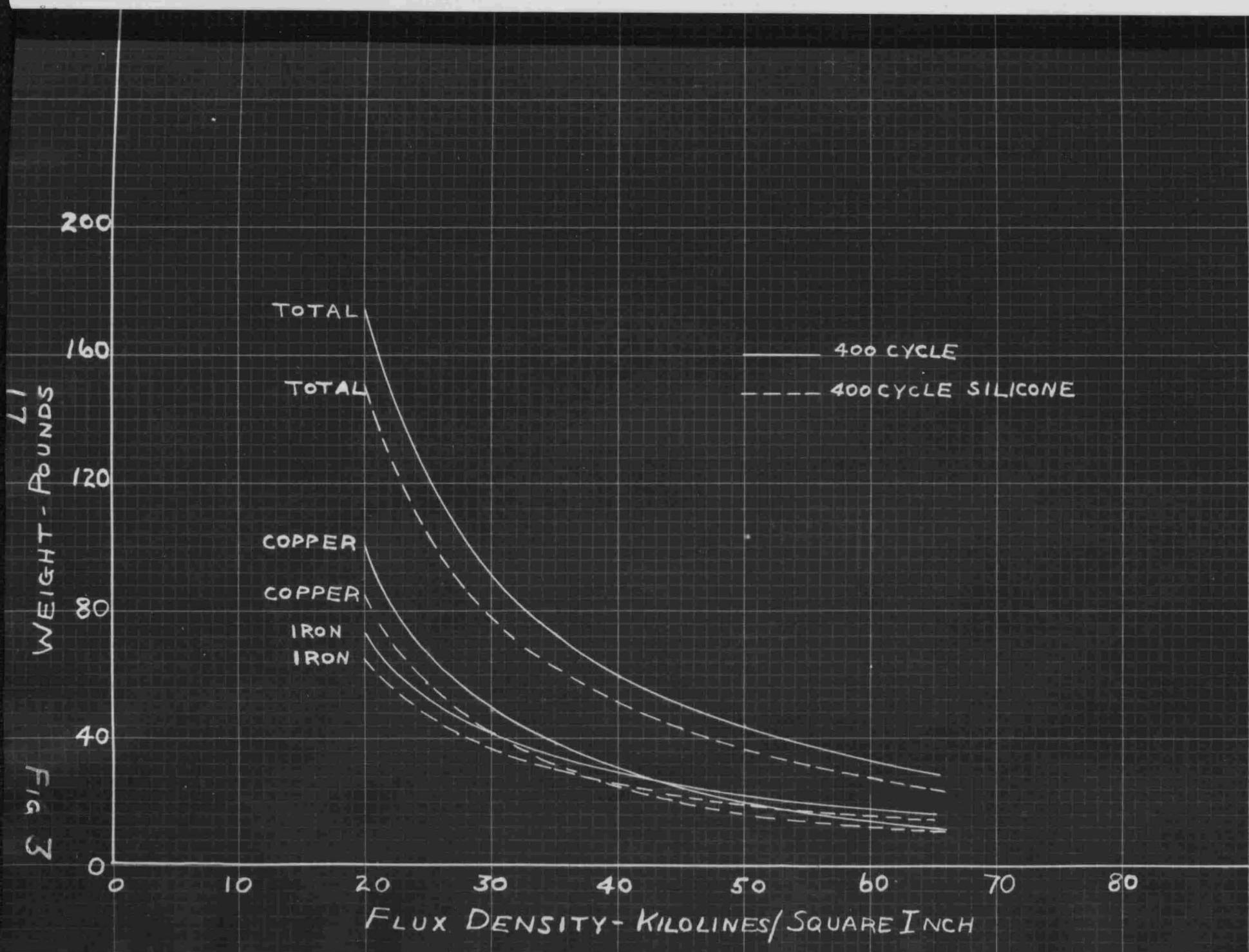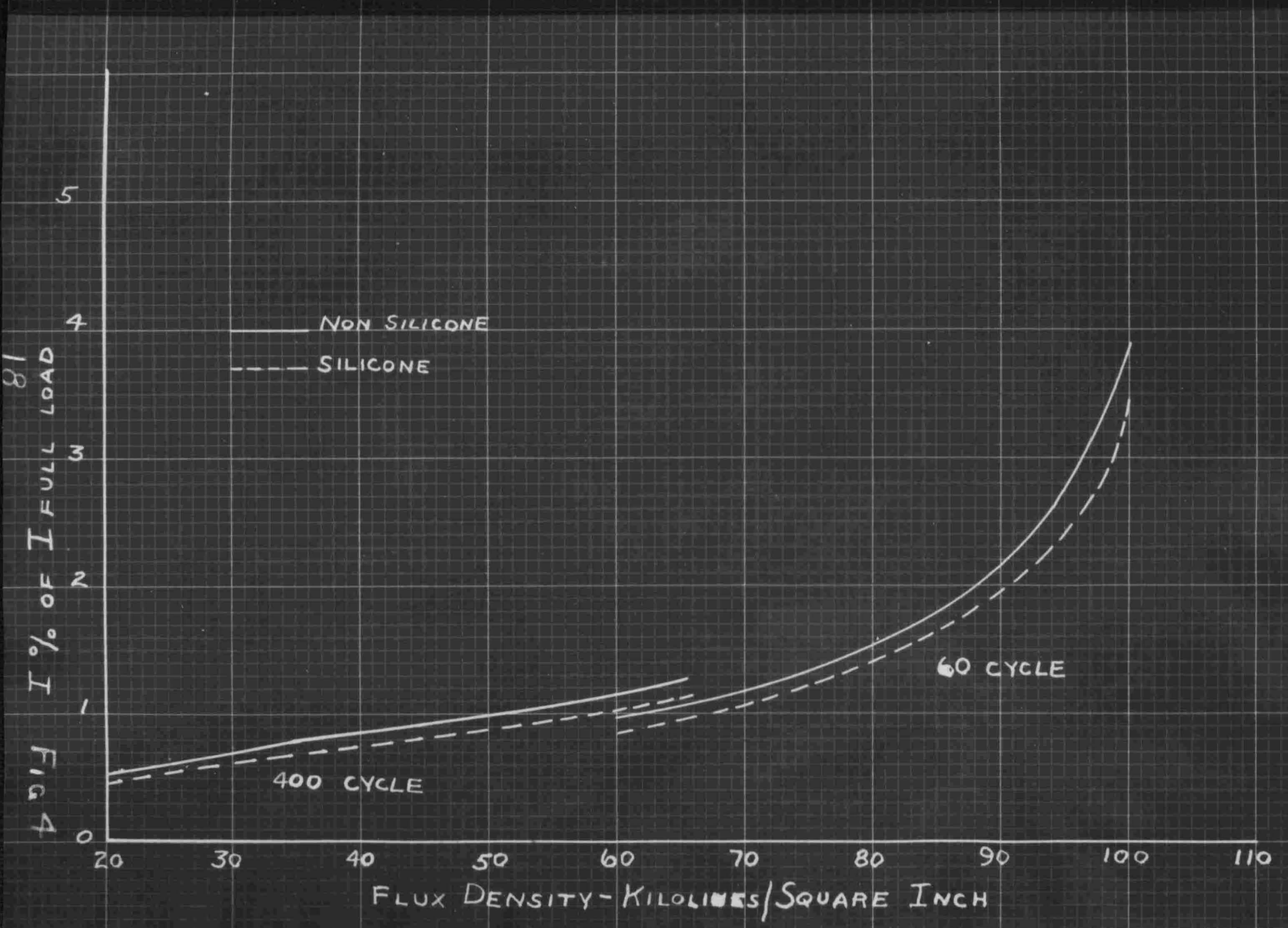
NON SILICONE
SILICONE

60 CYCLE

400 CYCLE

VOLUME — CUBIC FEET

FLUX DENSITY — KILOLINES/ SQUARE INCH

SAMPLE CALCULATIONS

1. Assume Flux Density equals 60,000 Lines/square inch.

2. Assume efficiency equals 99.16%.

3. Losses equal (1.00-.9916) X 10.000 which equals 84 watts. Core Losses equal Copper losses equal 42 watts.

4. From figure 6. watts/cubic inch for flux density of 60,000 is .083.

5. Volume of iron equals $\dfrac{\text{Core Loss}}{\text{Item 4}} = \dfrac{42}{.083} = 506$ in.^{3}

6. Dimensions of window are as follows:
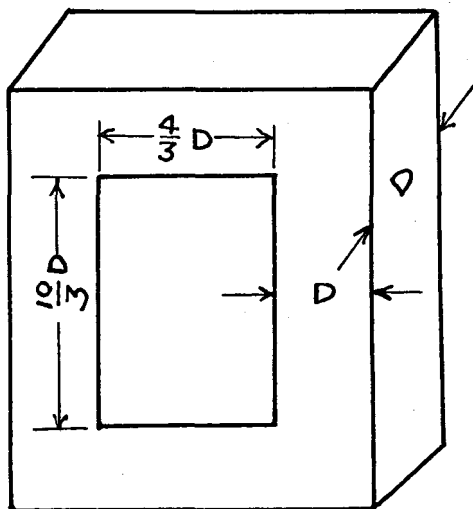
Assume stacking factor of .96
Then volume equals .96(20/3 D^3 plus 8/3 D^3 plus 4 D^3) or
Volume equals 12.8 D^3.

$$D^3 = \frac{\text{Item 5}}{12.8} = \frac{506}{12.8} = 39.5 \text{ in.}^3$$

7. D equals (Item 6)$^{1/3}$ = 39.5$^{1/3}$ = 3.406 in.

8. Window height equals 10/3D equals 10/3X3.406 = 11.353 in.

9. Window width equals 4/3D equals 4/3X3.406 = 4.54 in.

10. Assume clearance at top and bottom of coil of 1/4 inch.
Then coil height equals Item 8 - .5 equals 11.353 - .5 equals 10.853

11. From basic electrical considerations:

$$E = 4.44 \; NfBD^2K \times 10^{-8} \quad \text{or}$$

$$N = \frac{E \times 10^8}{4.44 \; f \; BD^2K} = \frac{450 \times 10^8}{4.44 \times 60 \times .96 \times BD^2} = \frac{176.5}{BD^2}$$

for two coils in series.

Then turns/coil N equals $\dfrac{176.5}{2 \; BD^2} = \dfrac{88.25}{BD^2}$

Turns/coil equal $\dfrac{88.25}{60,000 \times (3.406)^2}$ or 126.6 Turns/coil.

12. Coil Space $= \dfrac{\text{Item } 9 - 5 \times .25}{2}$ or $\dfrac{4.54 - 1.25}{2}$

or 1.645 in.

13. Assume width of inner coil equals .68 inch.

14. Mean Length of turn of inner coil equals:

4D plus 2Pi(.25 plus 1/2 width inner coil)

$= 4 \times 3.406 + 2Pi \; (.25 + 1.2 \times .68)$ or 17.334 inches

15. Copper Length inner coil equals Item 11 X Item 14 or

126.6 X 17.334 = 2195 inches

16. Resistance of Inner Coil:

Total Copper Loss equals 42 watts.

Copper Loss/Coil equals 42/4 watts $= I^2R = 10.5$ watts.

At full load I equals 10,000/450 or 22.25 amps.

Then $10.5 = (22.25)^2$ R and inner coil R $= .0212$ ohms.

17. R per inch of inner coil equals Item 16/Item 15 or $= \dfrac{.0212}{2195}$

or .00000967 ohms/inch.

18. Copper Cross section-Inner coil:

From Table 491 - Smithsonian Tables and other publications and Manuals (for checking purposes) The Resistance of hard drawn copper at 200° C is 17.80 ohms/circular mil foot or 1.4833 ohms/circular mil inch.

Then Cross Section $= \dfrac{1 \text{ X Pi}}{10^6 \text{ X Item 17 X 1.4833 X 4}}$

$$= \dfrac{1 \text{ X Pi}}{10^6 \text{ X .00000967 X 4 X 1.4833}} = .0549 \text{ in}^2$$

19. Assume 42 turns per layer and three layers of coils.

20. Inner coil conductor height with insulation equals Item 10/42

or 10.853/42 or .2585 inch.

Assume 5 mil silicone impregnated glass insulation, so copper height of conductor equals .2585 - 2 X .005 or .2485 inch.

21. Inner coil conductor width equals Item 18/ Item 20.

$$= \dfrac{.0549}{.2485} = .2205 \text{ inch.}$$

22. Total width inner coil equals 3 X Item 21 plus 3 X 2 X .005

$$= 3 \text{ X } .2205 \neq .03 = .6915 \text{ inch.}$$

23. Space for outer coil equals Item 12 - Item 22

$$= 1.645 - .6915 = .9535 \text{ inch}$$

24. Mean length of turn of outer coil equals:

4D $\neq$ 2Pi(.50 $\neq$ Item 22 $\neq$ 1/2 Item 23)

$= 4 \text{ X } 3.406 \neq 6.28 \ (.50 \neq .6915 \neq .4768)$ or 24.124 inches.

25. Copper length outer coil equals Item 11 X Item 24

$$= 126.6 \text{ X } 24.124 = 3050 \text{ inches.}$$

26. Resistance of outer coil equals Item 16 or .0212 ohm.

27. R/inch of outer coil equals Item 26/Item 25

$$= .0212/3050 = .00000695 \text{ ohms/inch.}$$

28. Copper area outer coil equals:

$$\dfrac{1 \text{ X Pi}}{\text{Item 27 X 1.4833 X 4 X } 10^6} = \dfrac{1 \text{ X } 3.1416}{.00000695 \text{ X } 10^6 \text{ X 4 X 1.4833}}$$

or .0762 square inch.

29. Same as Item 19- 42 turns/layer and three layers.

30. Outer coil conductor height equals Item #20 equals .2485 inch.

31. Outer coil conductor width equals Item 28/ Item 30

$$= \frac{.0762}{.2485} \text{ or } .3065 \text{ inch.}$$

32. Outer coil width equals 3 X Item 31 / .03

$$= 3 \text{ X } .3065 \text{ / } .03 \text{ or } .9495 \text{ inch.}$$

33. Same as Item 5 - 506 cubic inches of iron.

34. Weight of iron equals volume of iron in inches times weight or iron in pounds per cubic inch or Item 33 X .2763 or 506 X .2763 = 140 lbs.

35. Copper Density equals .322 pounds per cubic inch. Weight of copper equals 2 X .322 (Item 15 X Item 18 / Item 25 X Item 28) = 2 X .322 (2195 X .0549 / 3050 X .0762) = 227.5 lbs.

36. Length of mean flux path equals 2 X Item 8 / 2 X Item 9 / PiD

equals 2 X 11.353 / 2 X 4.54 / 3.14 X 3.406 = 42.506 inches.

37. Ampere turns per inch from Figure 3 equals .71.

38. Ampere turns per lap joint from Figure 4 equals 2.5.

39. Total ampere turns equal Item 36 X Item 37 plus 4 X Item 38

equals: 42.506 X .71 / 4 X 2.5 = 40.2 ampere turns.

40. $I_{mag} = \dfrac{\text{Item 39}}{2 \text{ X Item 11}} = \dfrac{40.2}{2 \text{ X } 126.6} = .159$ amps.

41. $I_{e/h}$ = Item 3/E equals 42/450 or .0933 amps.

42. $I_o = (I_{mag}^2 / I_{e/h}^2)^{1/2} = .184$ amps.

43. I_o - Percent of $I_{full\ load}$ equals Item 42 times 100 divided by $I_{full\ load}$.

$$= \frac{.184 \text{ X } 100}{22.25} = .827\%$$

44. Volume of transformer. Assume 2 inch clearance around periphery of coils and 2 inch clearance at both top and bottom.

Volume = Pi/4 X D^2h = $\dfrac{.7854}{1728}$ (16/3D / 4) (10/3D

/ 1 / 2 X Item 22 / 2 X Item 32 / 4)^2

$$= \frac{.7854 \text{ X } 22.16 \text{ X } 19.635^2}{1728} = 3.87 \text{ cubic feet.}$$

<u>45.</u>   Weight of iron and copper equals Item 34 plus Item 35 or

140 ≠ 227.5 = 367.5 pounds.

FIG 6

ARMCO TRAN-COR XXX
29 GAGE (.014)
60 CYCLE

FLUX DENSITY - KILOLINES/SQUARE INCH

CORE LOSS - WATTS / CUBIC INCH

25

Fig 7

Armco Tran-cor XXX
29 Gage (.014")
400 Cycle

Flux Density - Kilolines/Square Inch

Core Losses - Watts/Cubic Inch

26

Fig 8

Armco Tran-cor XXX
29 Gage - (.014")

R.M.S. Ampere Turns / Inch

27

FIG 9

ARMCO TRAN-COR XXX
29 GAGE (.014")

Flux Density - Kilolines/Square Inch

R.M.S. Ampere Turns/Lap Joint
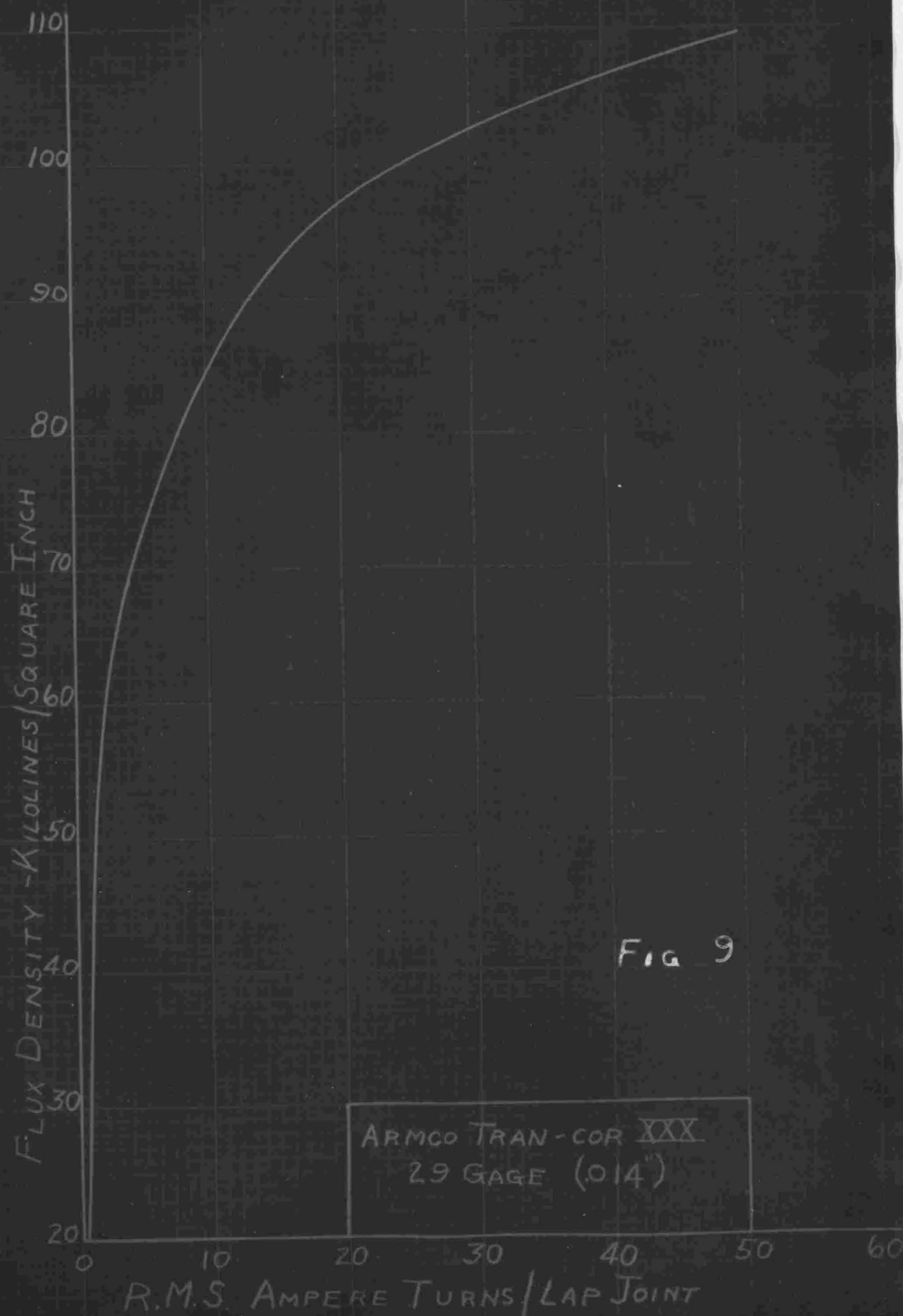
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